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New approaches to specifying performance of construction machinery

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Professional paper

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New approaches to specifying performance of construction machinery

The use of construction machinery for various construction processes must be based on the confrontation of actual conditions with the requirements for its maximum efficiency. The most important parameter for selecting construction machinery is its performance, which varies depending on its utilisation in specific conditions. Studies conducted so far show that the selection of construction machinery depends on a number of variables whose values are stochastic in nature. The present research aims at comparing the deterministic and stochastic approaches for the specification of technical and operational performance of construction machinery.

Key words:
construction machinery, performance of machinery, stochastic approach, deterministic approach

Stručni rad

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Novi pristupi u određivanju učinaka građevinskih strojeva

Izbor strojeva za različite građevinske radove mora se temeljiti na stvarnim uvjetima i postizanju njihove maksimalne učinkovitosti. Najvažniji parametar pri izboru građevinske mehanizacije jest specifikacija tih strojeva, koja ovisi o njihovoj primjeni u određenim uvjetima. Dosadašnja istraživanja pokazuju da izbor građevinskih strojeva ovisi o nizu varijabli čije su vrijednosti stohastičke prirode. Ovo istraživanje uspoređuje deterministički i stohastički pristup u specifikaciji tehničkih i planiranih učinaka građevinskih strojeva.

Ključne riječi:
građevinski strojevi, učinak stroja, stohastički pristup, deterministički pristup

Fachbericht

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Neue Verfahren zur Ermittlung der Leistung von Baumaschinen

Die Anwendung von Maschinen für verschiedene Bauarbeiten muss auf wirklichen Konditionen und dem Erzielen maximaler Effizienz beruhen. Der wichtigste Parameter bei der Auswahl von Baumaschinen bezieht sich auf Spezifikationen, die von der Anwendung unter verschiedenen Bedingungen abhängig sind. Bisherige Untersuchungen zeigen, dass die Auswahl von Baumaschinen durch eine Reihe an Variablen stochastischer Natur bedingt ist. Diese Untersuchung befasst sich mit dem Vergleich deterministischer und stochastischer Methoden zur Spezifikation technischer und planmäßiger Leistungen von Baumaschinen.

Schlüsselwörter:
Baumaschinen, Leistung von Baumaschinen, stochastische Verfahren, deterministische Verfahren

1. Introduction

The effective realization of construction works can hardly be imagined without mechanization. When managing a construction project (each construction process) we must address the issue of using construction machinery and equipment, especially in terms of their efficiency. Planning the needs for construction machinery begins at the preparation phase of construction projects. One of the basic tasks of production preparation is the specification for the use of specific types of construction machinery. The most important parameter for the selection of construction machinery is its performance. The performance of a machine is the basic characteristic that is used to determine whether it should be used on a particular project. The performance of a machine in terms of STN (Slovak Technical Standard) ISO 9245 (Earth-Moving Machinery, Machine Productivity, Vocabulary, Symbols and Units) [1] is measured by the volume of material processed per unit of time. Manufacturers of construction machinery have defined theoretical performance, which reflects the work of the machine in "ideal conditions". It is stated on the basis of calculation and experimental verification in the manufacturing business. It is also known as label performance and it is reported in the machine passports. The theoretical performance [2] is the maximum construction machine performance without disturbances, which in real conditions affect its performance. Therefore, the theoretical performance is the maximum performance that can be achieved on the basis of the machine kinematics in continuous operation, without time loss and breakdowns, and in optimum conditions. Theoretical performances are generally used only to compare performance of similar types of machines, taking into account their design.

The real-life performance of a construction machine reflects real conditions on the construction site. The real conditions generally reduce performance of construction machines. Technical performance is the maximum performance achievable in continuous operation under real conditions, at full use of the machine, with qualified control and maintenance. Technical performance reflects all impacts that influence the machine efficiency, and that must be considered to determine the need for the use of the machine. There are various reasons for the interruption of machine operation in real conditions.

The real performance of the machine, known as the operational performance denotes the value that corresponds to reality. The operational performance is the mean power of the machine achievable in concrete terms, affected by interruptions, which are directly related to the technology used and the work of the machine and its operator. For this purpose, additional factors and impacts are taken into account. The factors and impacts reflect conditions and operating status on the site, technical condition of construction machinery, level of organization of on-site work, weather, skills and motivation of personnel, and other. In the literature, the operational impacts are included in the rate of utilization coefficient (technical state of the machine and technological process for its use) and time use coefficient (working inaction of the machine) [2].

Several foreign sources have provided further definitions of the construction machinery performances. Karim and Marosszeky [3] define performance as the operational management accounting including financial and non-financial performance indicators. Karim and Marosszeky [3] state that the construction machinery performance is the process of re-thinking and re-evaluation of business processes to achieve significant performance improvements on projects. Reichelt and Lyneis [4] define the model that treats the project as a complex dynamic system. Al-Momani [5] states that the owner satisfaction with performance can be defined as the gap between what the owner expects and the level of performance the owner believes is being delivered by the contractors. Navon [6] defines performance as the comparison between the desired and actual performance. Ugwu and Haupt [7] classify the key performance indicators as site-specific and project-specific. A successful realization of construction projects (or their parts) depends largely on the performance of construction machinery. It is therefore necessary to make proper selection of construction equipment early at the planning stage of a construction project. Traditionally, the equipment used to be chosen by its performance, in terms of maximum productivity at lowest cost. A more accurate selection can be made by using the multi-criteria analysis to reach the final choice or recommendation. Casals et al. [8] define appropriate criteria and methods for the selection of construction equipment (Table 1). It is based on the notion that construction equipment should be selected according to its on-site performance.

Table 1. Steps of the methodology [8]

Criteria	Used analysis method
Optimum performance	Minimum hourly cost Maximum hourly productivity
Minimum risk	The minimum risk criteria will be the result of the sum of all applicable risks.
Minimum impact or environmental aspect	The minimum impact or environmental aspect will be the result of the sum of all applicable impacts. The valuation of these impacts was made through the method of identification and evaluation of environmental impact and aspects based on the Environmental Management Systems contained in the ISO 14001 standard.

Casals et al. [8] also define factors that influence construction machinery performance:

- Routine delays (factors that are derived from the inevitable equipment use, no machine can function at maximum power continuously).
- Restrictions to optimum mechanical operation (a reduction effect on production, due exclusively to limitations to its optimum operation).
- Site conditions (different kinds of factors can affect the performance).
- Direction and supervision (organization of the workflow, planning, and other management decisions, can pose obstacles to maximum performance).

Several studies have been conducted to develop various supporting tools aimed at optimizing the use of construction machinery. Milajić et al. [9] describe methodology for using genetic algorithms in solving problems of optimum task assignment to construction machinery operators, aimed at achieving maximum efficiency. Bezak and Linarić [10] created a methodological approach for calculating the hourly rate of earth-moving machines in construction industry. Dražić et al. [11] defined the factor that takes into account the unproductive operation phase of construction machines, within a comprehensive approach for optimizing the use of construction machinery. For this purpose, Izetbegović and Bezak [12] prepared the graphic-simulation model using the best-known software "Stroboscope". Other studies focus on the selection of machines and machine groups for various building processes from the standpoint of key optimisation criteria: quality, time and energy consumption [13-15]. Hewage et al. [16] point to the possibility of minimizing operational impact by increasing the workers' motivation within a comprehensive human resource management program. The results show that workers are committed to work only during 51 % of the total working time. The remaining time is used for preparatory activities (16 %), transfer to the site (8 %), instructions from supervisors (3 %), breaks (9 %), downtime (9 %), and other activities (4 %). These values indicate that the worker performance depends on the level of work organization and effectiveness of control activities on the site. Radziszewska-Zielina et al. [17] state that the machine performance is affected by technical capabilities of machines (engine and bucket capacity), by the influence of environment (soil loosening and weather conditions), and by factors affecting the operator (work comfort, health condition, stress, fatigue). According to results of this survey, the greatest impacts on the performance of construction machinery are associated with the psychophysical condition of the operator (experience, fatigue, health, and motivation) and technical parameters of the machine, and organizational factors. The performance is least affected by weather conditions.

The construction machinery significantly affects the cost of construction activities. The portion of construction machinery work varies on some construction projects from 10 to 50 percent, which is not insignificant in terms of economy of construction [18]. According to Assakkaf [19], up to 35 percent of the construction machinery costs are related to the maintenance and repairs. Savings in this item will be reflected in poor technical condition of the machine, reduced performance, poor quality of work, and increased risk of occupational injury, environmental accidents, increased intensity of downtime due to construction machinery breakdown, and other. As Abu Shaban [20] states, the construction machinery performance problem is costly and often results in disputes, claims, and affects development of the construction industry. Construction organizations must therefore have a clear mission and vision to formulate, implement, and evaluate performance of construction machinery. It is important for construction organizations to identify performance weaknesses in order to find appropriate solutions.

All this shows that the construction machinery performance is influenced by a variety of factors, many of which are random. Therefore, statistical methods based on probability theory can be used for its determination, in addition to currently used deterministic approaches. The present research aims at comparing the deterministic and stochastic approaches in order to determine the technical and operational performance of construction machinery.

2. Research methodology for specifying performance of construction machines

A real construction project served as the case study for determining the technical and operational performance of construction machines. The solution consisted of the following steps:

- Characteristics of construction process and machine parameters for the transport and placing of fresh concrete, in the scope of of realization of monolithic structures on a real construction project.
- Calculation of technical performance of construction machines for concrete works through deterministic approach based on technical specifications of construction machinery used, taking into account specific conditions on a real construction project. The stochastic approach also takes into account random interruptions of machine work.
- Determination of operational performance of construction machines through stochastic approach based on measurement of tower crane operating cycles, and through deterministic approach, using average duration of the working cycle.
- Comparison of data relevant to the technical and operational performances through Crystal Ball.

Stochastic models are based on the statistical series balancing principles, which express the quantitative characterization of random events through random variables. The scope of random variables varies in the given interval according to the probability distribution [21]. The processes and activities that are responsible for the random effects may be characterized by the Monte Carlo simulation. This method uses the Oracle Crystal Ball software. It allows users to specify random variables according to probability distributions [22], thus creating the stochastic models.

3. New approaches to determine performance of a construction machinery assembly

The comparison between deterministic and stochastic approaches is presented through the case study involving realization of the reinforced-concrete structure on the EcoPoint Office Center Košice construction project. Here, a real machine assembly work was used in the concreting process – tower crane with a concrete bucket and mixer trucks - concreting the third floor ceiling. The technical and operational performance of this assembly was determined by both deterministic and stochastic approaches. The following assembly was used in the concreting process:

- a tower crane POTAIN 15/15C with a concrete bucket (bucket weight: 300 kg, bucket capacity: 1 m^3)
- mixer truck Renault Kerax 375 with the nominal filling capacity of 8 m^3

Figure 1. Mixer truck transport flow

Route of filled mixer truck from the concrete batching plant to the construction site (red line: 1,7 km), and the route of the empty mixer truck from construction site to the concrete batching plant (blue line: 1,1 km), are shown in Figure 1.

3.1. Determination of machine-assembly technical performance using deterministic approach

In case of a cyclically operating machine, its technical performance is determined as a quotient, where the dividend represents the work done during one machine working cycle, and divisor represents the duration of one cycle:

$$Q = \frac{3600 \cdot q}{t_c} \quad [\text{m}^3/\text{h}] \qquad (1)$$

where:

- Q_t - is the technical performance [m³/h],
- q - is the amount of work done by the machine during one working cycle [m³],
- t_c - is the duration of one working cycle [s].

The calculation was based on specification of selected technical parameters of the machine assembly, taking into account specific conditions of the machine assembly use on the construction site:

- transport distances (1.1 km and 1.7 km, respectively),
- traffic situation along the mixer-truck driving route (city traffic),
- distances of vertical and horizontal transport by crane (third floor).

Technical parameters of the POTAIN 15/15C tower crane:

- vertical transport (lifting of load): 38,5 m/min
- horizontal transport (moving load along the boom): 58 m/min
- horizontal transport (boom turning): max. 0,8 rot./min
- vertical micro-transport: max. 3,5 m/min

The operational speeds of such transfers vary depending on the weight of the load and on technical parameters of the crane. The duration of the tower crane working cycle is presented in Table 2.

Table 2. Duration of working cycle for POTAIN 15/15C tower crane

Work activity of the tower crane	Duration of cycle [s]
Filling bucket with fresh concrete (t_1)	60
Transport of the full bucket to the concrete placing position + handling time (t_2)	70
Bucket emptying (t_3)	30
Transport of the empty bucket to the filling position + handling time (t_4)	51
Total t_c:	**211**

The POTAIN 15/15C tower crane transported 1 m³ of fresh concrete in one working cycle. When the duration of its working cycle is 211 seconds, the technical performance of the crane is 17.05 m³/h. Technical parameters of the Renault Kerax 375 mixer truck used in calculating duration of its working cycle (Table 3):

- average speed in city traffic: 30 km/h
- nominal filling capacity: 8 m³
- handling time (in a working cycle): 120 s
- drum emptying rate: 0-2 m³/min

Table 3. Duration of working cycle for the Renault Kerax 375 mixer truck

Work activity of the mixer truck	Duration of cycle [s]
Mixer truck filling	300
Transport of the full mixer truck (transport distance: 1,7 km, average speed: 30 km/h)	204
Mixer-truck emptying time(1)	1688
Transport of the empty mixer truck (transport distance: 1,1 km, average speed: 30 km/h)	132
Handling time	120
Total t_c:	**2444**

(1) *duration of emptying of the mixer truck is equal to 8 working cycles of tower crane*

The mixer truck transported 8 m³ of fresh concrete in one working cycle. When the duration of its working cycle is 2444 seconds, the technical performance of the mixer truck is 11.80 m³/h. The performance of the tower crane is especially important for smooth and continuous concreting. The performance is crucial for the performance of the whole machine assembly. Therefore, two mixer trucks have to be used to provide for the continuous supply of fresh concrete. The value of technical performance of the machine assembly is determined by the formula (2). The mentioned value is related to the deterministic approach, where the performance is determined based on technical specifications. Other effects, such as unevenly filled buckets, or any deviations in the amount of fresh concrete transported by different mixer trucks, are not considered in the calculation.

$$Q_t = \min(Q_{t1};\ x\ Q_{t2})\ [\text{m}^3/\text{h}] \tag{2}$$

$$Q_t = \min(17.05\ \text{m}^3/\text{h};\ 2 \cdot 11.80\ \text{m}^3/\text{h}) = 17.05\ [\text{m}^3/\text{h}]$$

where:
Q_t - is the technical performance of machine assembly [m³/h],
Q_{t1} - is the technical performance of tower crane [m³/h],
Q_{t2} - is the technical performance of mixer truck [m³/h],
x - number of mixer trucks [pcs].

3.2. Determination of machine-assembly technical performance using stochastic approach

In order to determine technical performance of the machine assembly through the stochastic approach, the real working cycles of the tower crane were measured on the EcoPoint Office Center Košice construction project. Then the set of resulting statistical data was processed using the Crystal Ball software. A selection of working cycles of the tower crane disaggregated into individual working activities is shown in Table 4.
The probability distribution had to be assigned to the data set in order to specify the data in a compatible spreadsheet editor as a random variable. The probability distribution defines all possible random-variable values and assigns the occurrence probability to every value. The Crystal Ball software assigns the probability distribution by statistical tests. The Anderson-Darling test in the "auto-select" mode was selected. The test assigned the statistical probability distribution to the set of data (Table 5).

Table 5. Probability distribution of random variables for individual working activities of the POTAIN 15/15C tower crane

Work activity of the tower crane	Probability distribution
Filling bucket with fresh concrete (ξ_{t1})	Poisson distribution
Transport of the full bucket to the position of concrete placing + handling time (ξ_{t2})	Hyper-geometric distribution
Concrete bucket emptying (ξ_{t3})	Binomial distribution
Transport of the empty bucket to place of filling + handling time (ξ_{t4})	Binomial distribution

These parameters were set before running the Crystal Ball software:
- confidence level: 95 %;
- number of trials: 100000;
- speed: extreme (redraw every 0,5 seconds).

Then the value of t_c was determined as the sum of the mean of the random variable values t_1 to t_4, obtained through the stochastic approach. After substitution into formula (3), the technical performance of the machine assembly is 17.50 m³/h as the mean of the random variable ξ_{Qt} (Figure 2). Forasmuch as the stochastic approach was applied, the result itself also presents the character of a random variable. In view of the fact that the stochastic approach solution was used, the result itself has also the character of a random variable.

$$E\xi_{Qt} = \frac{3600 \cdot q}{\xi_{t1} + \xi_{t2} + \xi_{t3} + \xi_{t4}}\ [\text{m}^3/\text{h}] \tag{3}$$

where:
$E\xi_{Qt}$ - is the mean of the random variable ξ_{Qt} [m³/h],
q - is the amount of work done by the machine during one working cycle [m³],
$\xi_{t1} \ldots \xi_{t4}$ - is the random variable of $t_1 \ldots t_4$ [s].

Table 4. Selection from the statistical data

Work activity of the tower crane	Number of measured working cycles of POTAIN 15/15C tower crane														
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
t_1 - filling bucket with fresh concrete [s]	81	89	77	79	80	49	49	57	64	51	44	58	63	54	65
t_2 - transport of the full bucket to the position of concrete placing + handling time [s]	61	65	68	57	61	56	58	66	57	56	54	47	54	55	58
t_3 - concrete bucket emptying [s]	34	30	25	28	33	16	33	22	17	29	32	18	25	28	34
t_4 - transport of the empty concrete bucket to the place of filling + handling time [s]	60	63	58	61	57	52	56	47	63	62	48	60	53	57	60
t_c – total time [s]	**236**	**247**	**228**	**225**	**231**	**177**	**196**	**192**	**201**	**198**	**178**	**183**	**195**	**194**	**217**

When comparing technical performance of the machine assembly specified through the deterministic approach (17.05 m³/h) with the technical performance of the machine assembly determined through the stochastic approach (17.50 m³/h), it can be concluded that the capacity utilization of the construction machine assembly was maximal just at the time of measurement. As the mentioned value is related to the stochastic approach, the considered conditions of the construction machine assembly use copied the real on-site situation.

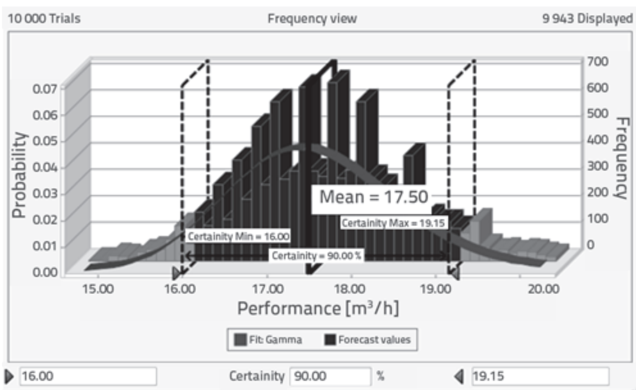

Figure 2. Result of simulation: Frequency view of random variable for technical performance of machine assembly (including basic statistical characteristics) in Crystal Ball

3.3. Determination of machine-assembly operational performance using deterministic approach

The technical performance of the machine assembly for a specific site, based on technical specifications of construction machinery used, taking into account specific conditions of construction activities, and determined by both approaches (deterministic and stochastic), is presented in previous sections of the paper. The planning and management of machine capabilities is a presumption that is in contrast with actual operational performance on the construction site. In practice, the operational performance of construction machines is more important. It includes all downtimes resulting from the machine operation. The selected tower-crane working cycles, disaggregated into individual work activities, including downtimes, are presented in Table 6. The individual work operations (t_1, t_2, t_3 and t_4), including downtimes (t_d) are considered when determining the operational performance of the machine assembly.

According to the deterministic approach, the operational performance of the machine assembly was calculated as an average value of t_c (from Table 6). In this case, it takes into account the downtimes (known as utilization coefficient, or the time use coefficient). Based on the presented data, and according to the formula (1), the operational performance of the machine assembly is 11.17 m³/h.

3.4. Determination of machine-assembly operational performance using stochastic approach

The determination of operational performance of the machine assembly through stochastic approach was made using the same settings of the Crystal Ball software. In this case, the probability distribution was assigned directly to t_c values (see Figure 3). This calculation included t_d values, eq. (4) was used:

$$E\xi_{Qt} = \frac{3600 \cdot q}{\xi_{tc}} \quad (4)$$

where:

$E\xi_{Qt}$ - is the mean of random variable ξ_{Qt} [m³/h],
q - is the amount of work done by the machine during one working cycle [m³],
ξ_{tc} - is the random variable of t_c [s].

The mean value of the machine-assembly operational performance, determined by simulation, is presented in Figure 4. It amounts to 11.21 m³/h.

Table 6. Selection from statistical data, including downtimes

Work activity of the tower crane	Number of measured working cycle of POTAIN 15/15C tower crane														
	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**	**11.**	**12.**	**13.**	**14.**	**15.**
t_1 - filling bucket with fresh concrete [s]	81	89	77	79	80	49	49	57	64	51	44	58	63	54	65
t_2 - transport of the full bucket to the concrete placing position + handling time [s]	61	65	68	57	61	56	58	66	57	56	54	47	54	55	58
t_3 - concrete bucket emptying [s]	34	30	25	28	33	16	33	22	17	29	32	18	25	28	34
t_4 - transport of the empty bucket to the place of filling + handling time [s]	60	63	58	61	57	52	56	47	63	62	48	60	53	57	60
t_d – downtimes [s]	0	0	0	0	0	1140	0	0	360	0	0	0	0	240	0
t_c – total time [s]	**236**	**247**	**228**	**225**	**231**	**1313**	**196**	**192**	**561**	**198**	**178**	**183**	**195**	**434**	**217**

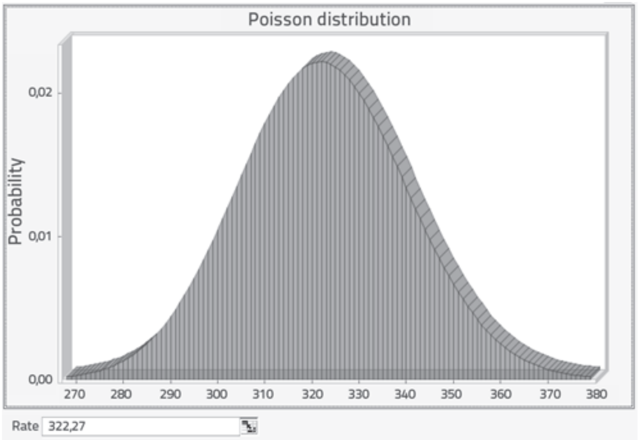

Figure 3. Probability distribution of random variable ξ_{tc} in Crystal Ball software

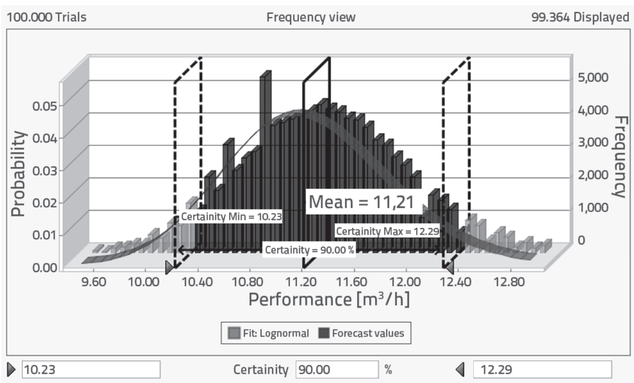

Figure 4. Simulation result: Frequency view of random variable for operational performance of machine assembly (including basic statistical characteristics) in Crystal Ball software

4. Comparison of approaches

When comparing resulting values of the technical and operational performance of the construction machine assembly, as determined by the deterministic and by the stochastic approach, with the value of real performance based on actually executed and recorded outputs by construction staff (see Table 7), it can be stated that values of the operational performance are converged to the value of real performance. It appears from this that statistical data (including downtimes) form a representative sample and reflect real conditions on the construction site. In addition, this paper draws attention to the fact that the prediction of downtimes is important for successful management of construction machines and assemblies. Obviously, it is not possible to measure repetitively the working cycles of construction machines and assemblies on each construction site for different construction machines and assemblies. In this context, construction companies can create databases showing performance of individual types of construction machines or assemblies. These data are absolutely necessary to make adjustments to particular conditions prevailing on individual construction projects. The data can be expressed through values of the coefficient (known as utilization coefficient, or time use coefficient), which represents the utilization of technical performance.

Table 7. Comparison of performance values

Performance \ Approach	Deterministic	Stochastic
Technical performance [m^3/h]	17.05	17.50
Operational performance [m^3/h]	11.17	11.21
Utilization of technical perform. [%]	66	64
Real performance [m^3/h]	11.28	

5. Conclusion

When comparing the stochastic approach with the deterministic approach on this particular project, it can be stated that performance values of both approaches are nearly equivalent. It can however be assumed that the statistical data sample is not large enough to exploit the advantages of Monte Carlo simulation. Despite of this, the stochastic approach is more accurate and reflects better actual on-site conditions. In cases where formulas and relations between variables are more complicated, it can be supposed that the potential of the stochastic approach (specifically the Monte Carlo simulation) will fully be used. Consequently, this approach can be applied in case of much more diverse input parameters, whereas the deterministic approach does not reflect randomness and probability of an event affecting performance of construction machines.

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